Intrinsically Passive Handling and Grasping

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Published in:
Technical Report on Automation for Meat, Fish and Poultry Cutting

Intrinsically Passive Handling and Grasping

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Abstract - **The paper presents a control philosophy called Intrinsically Passive Control, which has the feature to properly behave during interaction with any passive objects. The controlled robot will never become unstable due to the physical structure of the controller.**

1 Introduction

The environment with which a robot can interact is most of the times purely characterized. For humans a grasping task is often preceded by a grasping task planning, based on some visual sensing. The information based on the visual sensing gives the location of the object to be grasped, but does not contain any or little information concerning the object's material. For this reason, the grasping should be robust enough to ensure a proper behavior for a lot of different materials.

The act of interacting can be described using the concept of a power port [4]. Furthermore, as shown in [6], to ensure a stable behavior during interaction, the underlying control strategy should be such that the controlled system, as seen from the interaction energetic port, is passive.

A way to achieve this is by developing a controller which is passive by itself and whose action on the robot can be described as a physical interconnection with the system to be controlled. On the other hand, a problem with this approach is that in order to do something useful, the controlled robot should supply energy to the environment i.e. to move an object from a point p to a point $q \neq p$.

A way to combine these two apparently conflicting goals, can be found in *Physical Control* and the *IPC-Supervisor architecture* [6]. The term IPC stands for *Intrinsically Passive Control.*

An extra advantages of the presented techniques is that it is able to control interaction using only position measurements. This is important, since very often, force sensors are not available due to for example the sterility required in certain environments and velocity measurement are not present for reasons of costs.

An hypothesis is that the system to be controlled should be back-drivable and characterized by low friction.

The paper is organized as follows: in Sect. 2 the basic concepts behind the IPC-Supervisor architecture will be reviewed, in Sect. 4 a simple example for the use with a serial linkage is presented, in Sect. 5 the extension to a grasping device is presented, in Sect. 6 a laboratory set-up is illustrated and in Sect. 7 some conclusions will be drawn.

2 The IPC-Supervisor architecture

The basic idea about the IPC-Supervisor architecture is shown in Fig. 1. The system is composed of four parts: the environment with which the robot has to interact, the robot to be controlled, the IPC which controls the real time interaction and the supervisor which implements the high level part of the controller. All these parts are built in such a way that they can exchange energy through power ports. These ports are explained in the following section and are represented by half arrows, following the bond graph notation, in Fig. 1.

2.1 Power ports

The arrows connecting the various parts are called *power bonds* [6] and they represent the possible flow of physical energy between the elements of the controlled system.

A major concept which will be used in the paper, is the idea of a power port. A power port is the entity which describes the media by means of which subsystems can exchange physical energy with one another. A power port can be defined by the Cartesian product of a vector space V and its dual V^*:

$$P := V \times V^*$$

Elements belonging to P are pairs $(e, f) \in P$. The value of e and f are changing in time and shared by the two subsystems which are exchanging power through the considered port. The power exchanged at a certain time is equal to the intrinsic dual product:

$$\text{Power} = \langle e, f \rangle$$

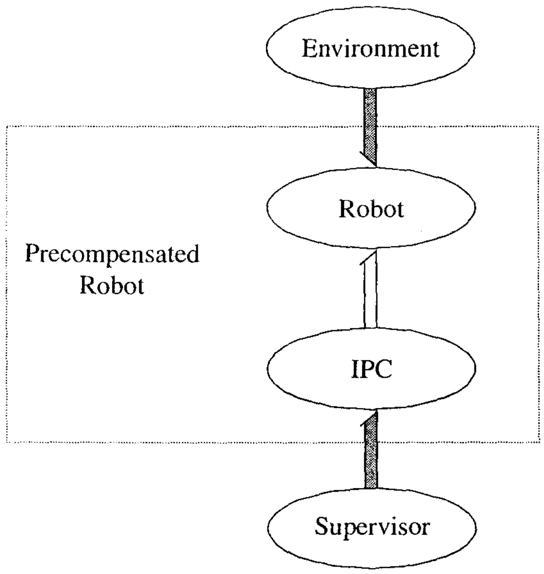

Figure 1: The general form of an intrinsically passive control scheme.

This dual product is intrinsic in the sense that elements of V^* are linear operators from V to $\mathbb{R}$, and therefore, to express the operation, we do not need any additional structure than the vector structure of V.

The direction of this power flow is indicated by the half arrow of the power bonds.

2.2 The IPC

The IPC is the most important part of the control. It is comparable to the local control of muscles implemented by the *muscle spindels*. This paper treats the IPC part of the controller. The energy stored by the IPC can only come either from the robot which is controlled or from the supervisor as shown in the figure. This implies that, if the supervisor does not supply any energy, the sum of the energy of the Robot and the IPC can only come from the environment which, being passive, has to be finite and cannot create instability to the controlled system.

2.3 The supervisor

The supervisor corresponds, in the human metaphor, to the human brain. By the supervisory part of the controller all the deliberative actions are started and planned. This paper does not treat this part of the complete controller which could also contain learning or artificial intelligence techniques.

3 Generalized Port Controlled Hamiltonian Systems

As also shown in [1], a numerical representation of a physical generalized Hamiltonian system with dissipation is:

$$\begin{aligned} \dot{x} &= (J(x) - R(x))\frac{\partial H}{\partial x} + g(x)u \\ y &= g'(x)\frac{\partial H}{\partial x} \end{aligned} \qquad (1)$$

where x is the state of the system, $J(x)$ is a skew-symmetric matrix called the *Poisson matrix*, $R(x)$ is a positive semi-definite matrix called the *dissipation matrix*, $H(x)$ is the *Hamiltonian* representing the physical energy contained in the system, $g(x)$ represents the input matrix, u is an input belonging to a vector space $\mathcal{V}$ and y is the output corresponding to the dual vector space $\mathcal{V}$. The power supplied to the system is instantaneously equal to $P = y^T u$.

Since the robot is a physical system, it can be modeled by equations of the form Eq. (1). Furthermore, as can be seen in Fig. 1, the robot has two power ports with which it can exchange energy with the environment and with the IPC. We can split the input $u^t = \begin{pmatrix} W^t & \tau^t \end{pmatrix}$ where W is the wrench applied to the end-effector of the robot and τ the torques applied to the joints, and the output $y^t = \begin{pmatrix} T^t & \dot{q}^t \end{pmatrix}$ where T is the twist of the end-effector and $\dot{q}$ the joints velocities. In this way $W^t T$ is equal to the physical power that the environment supplies to the robot and $\tau^t \dot{q}$ the physical power that the IPC supplies to the robot.

In an analogous way, the IPC can be chosen to have a form equal to Eq. (1) where $y^T = \begin{pmatrix} -\tau^T & E^T \end{pmatrix}$ and $u^T = \begin{pmatrix} \dot{q} & F^T \end{pmatrix}$ where $E^t F$ is equal to the power supplied by the supervisor to the IPC.

It can be seen that if the supervisor sets $F = 0$, no energy will be supplied to the pre-compensated robot and therefore the controlled system will stay passive during any interaction with a passive environment.

3.1 Advantages

The advantages of a controller of the explained form are many. First of all the system can be guaranteed to behave properly under contact with any kind on passive environment also if the environment is very unstructured like meet, rigid objects or others. Second, as shown in [8], the interaction can be properly controlled with only position measurements of the joints: no force measurements and no velocity measurements are required, and this can be very advantageous in environments where high hygiene is an issue as in the handling of meet or other kinds of food [2]. Last but not least, problems of actuator saturations which are always present in practice can be also easily coped by using the proposed techniques.

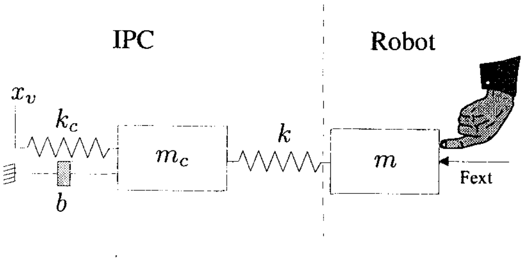

Figure 2: The IPC-Robot system of a serial linkage

3.2 Requirements

To be able to use these Hamiltonian techniques for control in the previously explained way without the need of force and velocity measurements, two major requirements are necessary. The first one is that the robot to be controlled should be back-drivable and with low friction. Secondly, collocated control can be implemented which means that we measure the positions of the joints in the same point where we actuate the torques.

3.3 Physical control

A way to approach the previous techniques is to think about a controller as a mechanical system which will be attached to the system to be controlled. The controller dynamics should have therefore the same dynamics of an equivalent physical system following Hogan's *Physical Equivalence* [3]. Two simple one dimensional examples will be treated in the following sections. The ideas here developed can be easily used in a completely geometrical three dimensional setting as it is done in [9, 7] using twists, wrenches and theory on Lie groups.

4 Serial linkages

To illustrate the application of the controller for a simple single limb manipulator, consider Fig. 2.

Suppose to have a one dimensional robot (a mass) which has to interact with a purely structure environment which applies a force F_{ext} to it. At the same time, we can apply by means of control a force on m. It can be shown that the physical system representing the controller of the example of Fig. 2 can be expressed in the form Eq. (1) [6]. If the supervisor does not supply any energy in a certain moment by keeping x_v constant ($\dot{x}_v = 0$), the energy of the system is equal to the kinetic energy of the robot (mass m) plus the energy of the controller which is composed of the potential energies of the springs k_c and k and the kinetic energy corresponding to the momenta of m_c. It can be seen that [5] if the stiffness k is much bigger than the stiffness k_c and the mass m is bigger

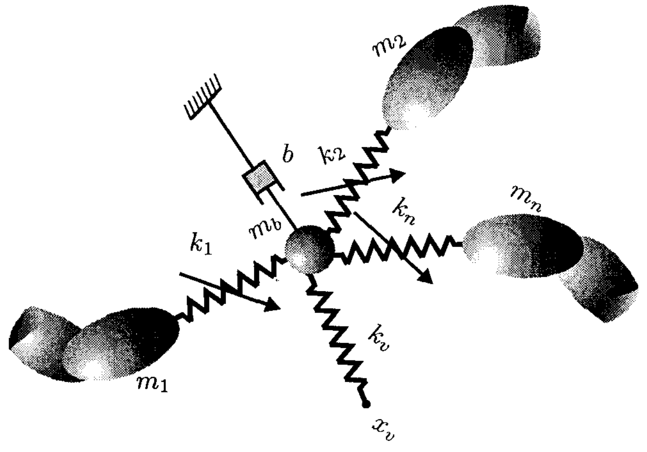

Figure 3: The IPC-Robot system of a parallel linkage

than the mass m_c, the energy supplied by the environment "will travel" through the mass m, the spring k and the mass m_c to be eventually dissipated in b, and this is done without measuring the velocity of the mass m !

For a three-dimensional serial linkage, the controller can be thought of as being a mechanical system attached to the end-effector of the robot. The equivalent wrench that the controller would apply to the end-effector of the linkage can be easily mapped with the transposed Jacobian to the torques to be applied to the joints.

5 Parallel linkages and grasping

The previous techniques can be easily extended to a multi-linkage system like cooperating robots or a robotic hand [9]. The concepts used here are the same as in the previous section, but now we have to deal with more "end-effectors" end the coordination between them. In Fig. 3 $m_1, .., m_n$ denote the end effectors of the multi-linkages to be controlled like the tips of the fingers of a robotic hand.

By means of changing the rest length[1] of the springs $k_1, .., k_n$ by the supervisor, the relative positions of the fingers can be controlled. Furthermore, by modifying x_v, the total robotic hand can be moved. The damper b makes the system asymptotically stable. Note again that only the positions of $m_1, \ldots, m_n$ are necessary to implement a controller with the desired dynamics.

Even if only position measurements are needed, overall dissipation is achieved because of the presence of the viscous term connected to the object m_b which is called *virtual object*. The viscous force is applied to the virtual object as shown in Fig. 3. Any energy entering the control system which causes a motion of the virtual object is dissipated, and

[1] The rest length of the springs is their length corresponding to a minimum of stored energy.

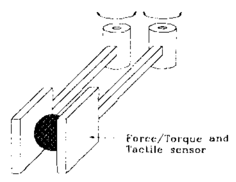

Figure 4: Experimental setup.

this has a nice physical interpretation. Again, note that this is achieved without the necessity to measure velocities of the robotic system.

The forces generated by the controller's springs $k_1, \ldots, k_n$ can than be converted to joint torques using the transposed Jacobian.

6 Experimental Set-Up

A laboratory setup has been used for the evaluation of the control technique described in the previous Section. The setup, schematically shown in Fig. 4, consists of two one-dof "fingers" equipped with position, force/torque and tactile sensors, [9]. The last sensors are just used for collecting data and not for control purposes.

The block-diagram of the control scheme used in the experiment is shown in Fig. 5. As discussed above, only position measurement is used in the control loop (x_1, x_2): force/torque and tactile information are acquired only in order to show the features and the performances of the overall control scheme.

The experimental results which are reported in [9] have shown the proper functioning of the idea.

7 Conclusions

In this paper the concepts of physical intrinsical passive control have been introduced. Stable behavior with a completely unstructured environment can be only ensured with the presented techniques because they directly consider the physical structure of the system and its exchange of energy with the environment.

References

[1] M. Dalsmo and Arjan van der Schaft. On representations and integrability of mathematical structures in energy-conserving physical systems. *SIAM Journal of Control and Optimization*, 37(1):54–91, 1999.

[2] M.J. de Krijger, W.T.C. van Luenen, S.T. Pedersen, and S. Stramigioli. Reliable assembly of products using an impedance controlled manipulator. In *Proc. American Control Conference1997*, Albuquerque, New Mexico, June 1997.

[3] Neville Hogan. Impedance control: An approach to manipulation: Part I-Theory. *ASME J. ofDynamic Systems, Measurement and Control*, 107:1–7, March 1985.

[4] Henry M. Paynter. *Analysis and Design of Engineering Systems*. M.I.T. Press, Cambridge, Massachusetts, 1960. Course 2.751.

[5] Stefano Stramigioli. Creating artificial damping by means of damping injection. In K.Danai, editor, *Proceedings of the ASME Dynamic Systems and Control Division*, volume DSC.58, pages 601–606, Atlanta, (GE), 1996.

[6] Stefano Stramigioli. *From Differentiable Manifolds to Interactive Robot Control*. PhD thesis, Delft University of Technology, Delft, The Netherlands, December 4 1998. ISBN 90-9011974-4, `http://lcewww.et.tudelft.nl/~stramigi`.

[7] Stefano Stramigioli. *Stability and Stabilization of Nonlinear Systems*, chapter A Novel Grasping Strategy as a Generalized Hamiltonian System, pages 293–324. Lecture Notes in control and Information Sciences. Springer, London, 1999.

[8] Stefano Stramigioli, Bernhard Maschke, and Arjan van der Schaft. Passive output feedback and port interconnection. In *Proc. Nonlinear Control Systems Design Symposium1998*, Enschede, The Netherlands, July 1998.

[9] Stefano Stramigioli, Claudio Melchiorri, and Stefano Andreotti. A passivity-based control scheme for robotic grasping and manipulation. In *Proceedings of the International conference of Decision and Control*, Phoenix, December 1999.

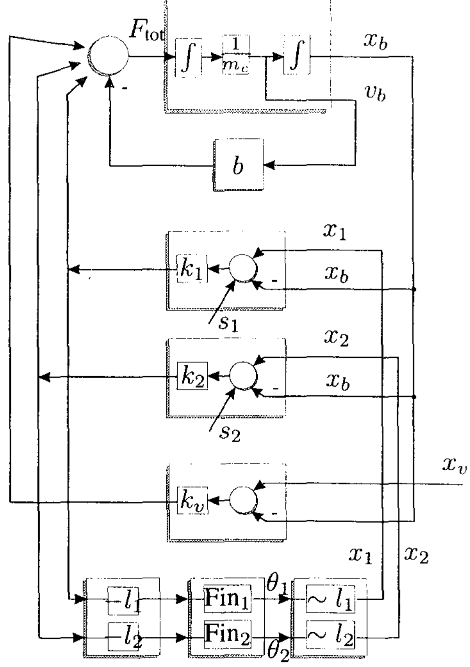

Figure 5: The implemented control schema